Room Temperature Continuous Wave Lasing in Nanopillar Photonic Crystal Cavities

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Abstract: We demonstrate room temperature continuous wave lasing in bottom-up photonic crystal cavities formed by patterned III-V nanopillars. Single-cell high-Q photonic crystal cavities are formed with nanopillars by selective-area epitaxy. Control of the nanopillar geometry and heterostructures allows for high-Q and large confinement factor, resulting in a low threshold power density of 75 W/cm^2 at 1040 nm emission wavelength.

OCIS codes: (230.5298) Photonic crystals; (140.3945) Microcavities

1. Introduction

Continuing development in the area of nanowire (NW) and nanopillar (NP) based optoelectronic devices has grown dramatically in recent years. The ability to control the formation of axial and radial heterostructures during growth, as well as the ability to grow on large lattice mismatched substrates such as Silicon has been a large motivating factor[1]. However, the demonstration of low threshold lasers with NWs or NPs as the active gain medium has been limited due to difficulty in design and fabrication of high quality optical cavities. Furthermore, the small diameters of these semiconductor nanostructures results in high surface recombination rates. Here, we present a method of fabricating photonic crystal (PhC) cavities with selective-area epitaxy of III-V NPs. The ability to control position, diameter, axial and radial heterostructures allows for the formation of high-Q cavities with low-threshold capable of continuous wave lasing at room temperature.

2. Design and fabrication

The design of the NP-PhC cavities is shown in Fig 1. The NPs are embedded in low index polydimethylsiloxane (PDMS) with one side of the cavity exposed to air. The NPs are arranged in a triangular lattice with a radius to pitch ratio (r/a) of 0.2 to ensure a wide photonic band gap. Five rows of NPs are shifted towards the center of the cavity as shown in Fig 1a. The shift factors resulting in the optimum cavity Q of 10,700 is shown in Fig 1b. The E-field intensity of the resulting mode is shown in Fig 1c.

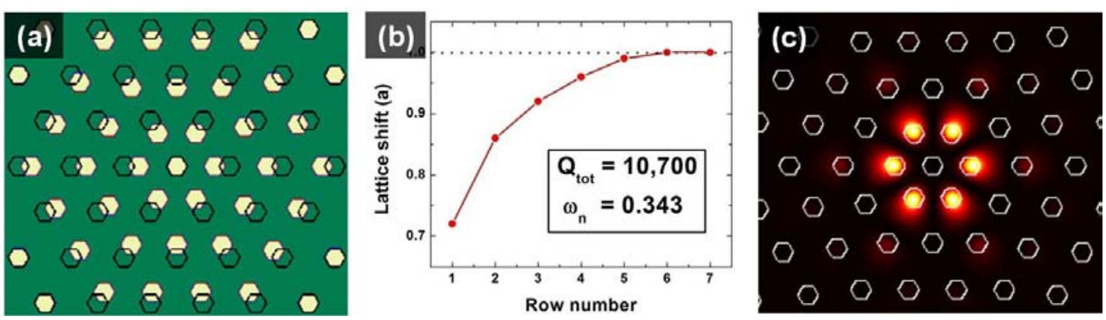

Figure 1. Design of high-Q PhC cavities composed of NPs. (a) Rows of NPs surrounding the center of the cavity are shifted towards the center to form a single resonant mode. (b) The lattice shift in units of lattice constant **a** for each row of the cavity for maximum Q. (c) E-field intensity of the cavity mode.

The NPs forming the PhC lasers are grown by selective-area metal-organic chemical vapor deposition on masked GaAs substrates[2]. The NPs implement a GaAs/InGaAs/GaAs axial double heterostructure for accurate placement of gain with the the cavity[3] and InGaP shells to reduce surface recombination[4]. Fig 2a shows the NP-PhC cavities embedded in PDMS with a close-up view showing the axial and radial heterostructures. This design allows for excellent overlap between the InGaAs gain region and the peak E-field intensity of the cavity mode.

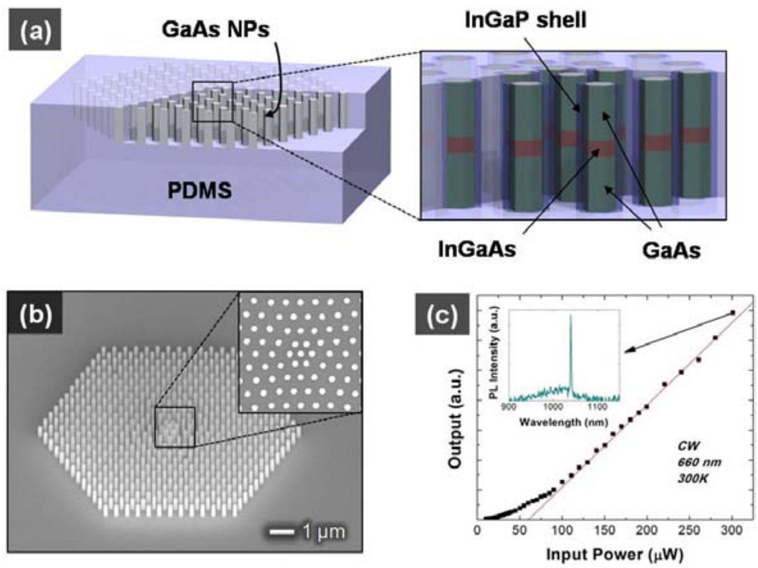

Figure 2. (a) Schematic of the NP-PhC in PDMS with close-up showing the GaAs/InGaAs/GaAs axial heterostructure with InGaP shells. (b) 45° tilted SEM of a NP-PhC cavity as grown on the GaAs substrate with a magnified top-down view of the cavity region. (c) *L-L* curve of a NP-PhC laser under continuous excitation at room temperature with inset showing the output spectrum at $5\times L_{th}$.

3. Results

A NP-PhC cavity as grown on the GaAs substrate is shown in Fig 2b. The inset shows a top-down view of the cavity matching the high-Q design shown in Fig 1. Based on growth rate calibrations, the GaAs segments are estimated to be 200 nm in height, with the center InGaAs segment ~130 nm in height. With an experimental cavity Q of ~8000 and a simulated confinement factor of $\Gamma = 0.328$, the required threshold gain for lasing is calculated to be $g_{th} = 76$ cm^{-1}.

The experimental demonstration of continuous wave lasing at room temperature is shown in Fig 2c. The *L-L* curve spans from $0.2\times L_{th}$ to $5\times L_{th}$ where $L_{th} = 60$ µW. With a 10 µm diameter spot size of the excitation laser, the resulting threshold power density is 75 W/cm^2. Above a maximum input power of 300 µW the NPs quickly degrade due to heating as a result of the relatively low thermal conductivity of PDMS. The inset of Fig 2c shows the output spectrum above threshold with the peak emission wavelength at 1040 nm.

In conclusion, we have demonstrated room temperature continuous wave lasing in NP-PhC cavities. The low threshold power achieved is a result of accurate control of the NP heterostructures and geometry. These lasers embedded in PDMS can be useful as internal light sources in for spectroscopy in microfluidic and biosensing systems. Future work will explore use of transparent conducting oxides (TCOs) as contacts for electrically injected lasers.

4. References

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